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SPRAY CHARACTERIZATION OF ULTRA-LOW–VOLUME SPRAYERS TYPICALLY USED IN VECTOR CONTROL[1]

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ABSTRACT. Numerous spray machines are used to apply pesticides for the control of human disease vectors, such as mosquitoes and flies, and the selection and setup of these machines significantly affects the level of control achieved during an application. The droplet spectra produced by 9 different ultra-low–volume sprayers with oil- and water-based spray solutions were evaluated along with 2 thermal foggers with the use of diesel-based spray solutions. The droplet spectra from the sprayers were measured with the use of laser diffraction droplet sizing equipment. The volume median diameter from the sprayers ranged from 14.8 to 61.9 µm for the oil-based spray solutions and 15.5 to 87.5 µm for the water-based spray solutions. The 2 thermal foggers generated sprays with a volume median diameter of 3.5 µm. The data presented will allow spray applicators to select the spray solution and sprayer that generate the droplet-size spectra that meet the desired specific spray application scenarios.

KEY WORDS Atomization, droplet size, sprayer, ULV sprays, vector control

INTRODUCTION

One of the most common methods for controlling arthropod vectors, particularly mosquitoes, is the application of insecticides by either ground or aerial sprayers. Ultra-low–volume (ULV) sprayers are some of the most commonly used sprayers for control of these insects (Rathburn 1972; Linley and Jordan 1992, Matthews 1996, Rose 2001). When selecting application equipment and insecticides, applicators depend on recommended equipment operating parameters, as supplied by the manufacturer, along with recommended application rates and droplet sizes as detailed by chemical labels to ensure the most efficacious application. For vector control with space sprays, the droplet size should be less than 30 µm volume median diameter ($D_{V0.5}$; Ledson and Matthews 1992; WHO 2006a, 2006b). As droplet size is 1 of the most significant factors affecting the success of vector control applications, it is critical to know baseline droplet and spray cloud characteristics for the equipment used.

Many vector control pesticide labels provide users with droplet-size requirements that generally fall between 8 and 30 µm $D_{V0.5}$ with at least 90% of the volume contained in droplets less than 50 µm. To comply with these labels, the user must select and/or adjust sprayers to produce droplets that meet these requirements. Providing that droplet-size data and guidance to meet these label requirements was a primary objective for conducting the testing that is reported in this manuscript. Another objective of this study was to use a laser-diffraction droplet analysis system to obtain baseline droplet and spray cloud formation information on available spraying equipment that is either already incorporated or could be incorporated into Department of Defense (DoD) pest management programs. This would provide program managers with the information that would allow them to select the best sprayers for their particular needs.

MATERIALS AND METHODS

A total of 30 replicated spray tests, comprised of 9 sprayers and 4 solutions, were completed for this study. The sprayers were selected from ULV equipment that is commonly used for vector control applications. The specific testing protocol, spray formulations, equipment tested, and physical property measurement procedures are discussed in the following sections.

Measuring droplet sizes

For each combination of sprayer and spray formulation, at least 3 independent replications were conducted. For each replication, the Sympatec laser system was positioned approximately 2 m from the outlet of the sprayer (Fig. 1). The spray cloud was directed through the laser beam for 10–20 sec, during which time droplet-size measurements of the spray cloud were made. The time that the spray cloud was directed through the optical path of the laser varied between sprayers, depending on the width of the spray

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Fig. 1. Testing of ultra-low–volume fogging atomizer equipment. Spray from the nozzle is passing through the laser, which measures the spray droplet size.

plume generated by the sprayer. For each replication, the entire spray plume for each sprayer was measured (Standard E1260, ASTM 2005). Appropriate personal protective equipment, such as respirators, gloves, goggles, and Tyvex suits, were worn during all tests containing active ingredients.

Droplet sizing system

A Sympatec Helos laser diffraction droplet sizing system (Sympatec Inc., Clausthal, Germany) was utilized in this study. The Helos system uses a 623 nm He–Ne laser and was fitted with an R5 lens, which made the dynamic size range from 0.5 to 875 µm in 32 sizing bins. The authors found that when using the laser system outdoors, the last channel (i.e., sizing bins) of the Helos system should be turned off or not factored into the droplet-size measurement results. This channel represents the largest droplet size and tends to pick up some noise or random signals, possibly from equipment vibration or scattered ambient light. With this channel turned off, the dynamic range of the instrument is from 0.5 to 735 µm. These channels are not turned off if any droplets are measured within 2 sizing bins of the smallest turned-off channel. For these studies, this criterion meant that no droplets greater than 515 µm in diameter were measured during any of the atomization tests.

The spray droplet-size data were determined and reported as a mean and standard deviation corresponding to the data measured during the 3 replications for each combination of sprayer and pesticide. Means and standard deviations of the volume median diameter (VMD or $D_{V0.5}$), $D_{V0.1}$, and $D_{V0.9}$ were determined. The $D_{V0.5}$ is the droplet diameter (µm) where 50% of the spray volume is contained in droplets smaller than this value (Standard E1620, ASTM 2004). Similarly, the $D_{V0.1}$ and $D_{V0.9}$ values are the diameters at which 10% and 90%, respectively, of the spray volume is contained in droplets of this size or less. The percent of spray volume contained in droplets less than 20 µm (%Vol $<$ 20 µm) was calculated for all tests, as it allows the equipment user to determine the portion of the applied material that will most likely stay aloft after an application and potentially impinge on flying insects.

Spray formulations

Four spray formulations were tested: (1) BVA 13 ULV Oil (Severely Hydro-treated Paraffinic Oil, Adapco Inc., Sanford, FL), (2) water with 0.2% volume/volume addition of a nonionic surfactant (R-11, Wilbur-Ellis Co., San Antonio, TX), (3) diesel (automotive grade), and (4) diesel (automotive grade) with 2 insecticides diluted at 1:39–1:195 ratios. The 2 insecticides that were diluted were Fyfanon® ULV (malathion, Cheminova A/S, Lemvig, Denmark) diluted at 1:91.5, and Kontrol® 30–30 (permethrin and piperonyl butoxide, Univar USA, Inc., Austin, TX) diluted at 1:39 and 1:195. The dilutions were chosen as representative of those commonly used in vector control applications.

Equipment

Nine ULV sprayers and 2 thermal fogging units, as described below, were evaluated in this study.

- Clarke ULV-P1 (Clarke Mosquito Control, Rosella, IL). Study notation: Clarke P1. Description: Handheld. The P-1 ULV sprayer is a blower-pressurized system driven by a Robin 4-cycle engine with a net weight of 18.5 lb (8.4 kg). It has 4 adjustable flow rate settings (1/4, 1/2, 3/4, and full) and a maximum flow rate of 2.0 oz/ml (60 ml). The dimensions of this piece of equipment are 16 in. long × 14 in. wide × 21 in. high (41 cm long × 36 cm wide × 53 cm high).
- Curtis Dyna-Fog® Maxi-Pro™ 4 (Curtis Dyna-Fog Ltd., Westfield, IN). Study notation: CDF Maxi-Pro 4. Description: Truck mounted. The Maxi-Pro 4 ULV Aerosol Applicator is powdered by an 18-hp, 4-cycle, Briggs & Stratton gasoline engine with an electric start. This engine powers a positive displacement rotary blower by a direct drive. This machine has a net weight of 426 lb (194 kg), and a maximum flow rate of 25 oz/min (591 ml). The dimensions of this piece of equipment are 44 in. long × 37 in. wide × 30 in. high (112 cm long 94 cm × 76 cm high).
- Curtis Dyna-Fog® Dyna-Jet® Model L-30 (Curtis Dyna-Fog Ltd., Westfield, IN). Study notation: CDF L-30. Description: Truck mounted. The L-30 is an all-electric, lightweight ULV sprayer that produces a pesticide droplet spectrum by the use of a high speed, rotary atomizer with the resulting aerosol being dispersed by an axial fan. This ULV generator has a net weight of 105 lb (48 kg) and a maximum flow rate of 14 oz/min (414 ml). The dimensions of this piece of equipment are 44 in. long × 29 in. wide × 39 in. high (112 cm long × 74 cm wide × 99 cm high).
- Curtis Dyna-Fog® Mini-Lite™ (Curtis Dyna-Fog Ltd., Westfield, IN). Study notation: CDF Mini-Lite. Description: Truck-mounted. The Twister ULV/Mister is powered by a Tanaka 1.8-hp (40 cc), 2-cycle, gasoline engine. The engine drives a high-speed rotary-type blower, which provides the air blast that creates the pesticide droplet spectrum at the Microtec™ nozzle. This sprayer has a net weight of 29 lb (13 kg), and a maximum flow rate of 17 oz/min (133 ml). The dimensions of this piece of equipment are 15 in. long × 15 in. wide × 28 in. high (38 cm long × 38 cm wide × 71 cm high).
- Curtis Dyna-Fog® Anileator™ (Curtis Dyna-Fog Ltd., Westfield, IN). Study notation: CDF Anileator. Description: Handheld. The Anileator is a 110-volt electric, lightweight ULV sprayer that utilizes a blower and a 3-nozzle atomization system to produce its droplet spectrum. This ULV generator has a net weight of 7 lb (3 kg) and a maximum flow rate of 4 oz/min (127 ml) for water-based compounds. The dimensions of this piece of equipment are 10 in. long × 10 in. wide × 14 in. high (25 cm long × 25 cm wide × 36 cm high).
- ADAPCO Guardian ULV 190 ES (ADAPCO, Sanford, FL). Study notation: ADAPCO Guardian 190ES. Description: Truck mounted. The Guardian 190 ES ULV Aerosol Generator is powered by a Kawasaski 19 hp (41.19 cu. in.), 4-cycle, overhead-valve, V-twin cylinder gasoline engine with an electric start. This engine drives a Gardner Denver blower that provides the air blast that creates the pesticide droplet spectrum at the vector air atomization system nozzle. This ULV aerosol generator has a net weight of 510 lb (232 kg) and a maximum flow rate of 20 oz/min (591 ml). The dimensions of this piece of equipment are 45 in. long × 37 in. wide × 30 in. high (114 cm long × 94 cm wide × 76 cm high).
- Birchmeier® B245 Backpack Sprayer with an iGEBA® ULV nozzle (Birchmeier Sprühtechnik AG, Stetten, Germany & IGEBA Geraetebau GmbH, Weitnau, Germany). Study notation: Birchmeier B245. Description: Backpack. The B245 is powered by a 3.1-hp, 2-cycle, gasoline engine. The engine drives a

Table 1. Atomization parameters for oil-based spray solutions.

Sprayer	Rate (oz/min)	Pressure (psi)	$D_{V0.1}$ (μm ± SD)	$D_{V0.5}$ (μm ± SD)	$D_{V0.9}$ (μm ± SD)	Vol < 20 μm (%)
Birchmeier B245: ULV Nozzle	4	Fixed	16.2 ± 0.1	45.0 ± 0.9	79.2 ± 1.6	15.7
Birchmeier B245: LV Nozzle	4	Fixed	11.5 ± 0.1	38.8 ± 1.2	70.0 ± 1.6	23.2
ADAPCO Guardian 190ES	4	5	7.1 ± 0.9	14.8 ± 1.3	30.3 ± 4.9	70.8
ADAPCO Guardian 190ES	10	5	8.5 ± 0.5	16.8 ± 0.6	30.8 ± 1.1	63.3
B&G Porta-Pak	2.4	Fixed	18.3 ± 0.7	61.9 ± 2.1	112.0 ± 1.8	11.5
CDF MiniLite	4	Fixed	6.5 ± 1.2	17.9 ± 0.4	36.4 ± 0.5	56.8
CDF L30	4	Fixed	2.6 ± 0.4	25.7 ± 0.7	41.2 ± 0.5	32.4
CDF Anileator	4	Fixed	10.1 ± 1.5	39.1 ± 1.5	79.8 ± 1.8	25.1
Clarke P1	1	Fixed	10.0 ± 0.7	35.0 ± 1.6	66.5 ± 5.8	29.0
CDF Maxi-Pro 4	4	4	7.5 ± 0.3	20.3 ± 0.0	42.3 ± 0.3	49.0
CDF Maxi-Pro 4	4	6	7.8 ± 0.1	15.3 ± 0.1	29.3 ± 0.2	69.5

blower that creates the air blast that produces the pesticide droplet spectrum at the nozzle. This sprayer has a net weight of 27 lb (12 kg), and a maximum flow rate of 17 oz/min (133 ml). The dimensions of this piece of equipment are 54 in. long × 18 in. wide × 28 in. high (137 cm long × 46 cm wide × 71 cm high). This unit has 2 nozzle options: 1) LV nozzle: Low-volume nozzle with impellers in the outlet of the airstream (this nozzle was orange), 2) ULV nozzle: Ultra-low–volume nozzle with impellers in the outlet of the airstream (this nozzle was silver). For these tests, the flow rate on both nozzles was set to 4 oz (120 ml)/min.

- Arro-gun Mozzie 250 HO (Arro-gun Spray Systems, L.L.C., Reno, NV). Study notation: Arro-Gun Mozzie. Description: Truck mounted. The Mozzie is an all-electric ULV sprayer that uses a blower that creates an air blast that produces the pesticide droplet spectrum at the 2-nozzle system. This ULV generator has a net weight of 170 lb (77 kg) and a maximum flow rate of 19 oz/min (562 ml). The dimensions of this piece of equipment are 42 in. long × 21 in. wide × 40 in. high (107 cm long × 53 cm wide × 102 cm high).
- Phoenix Fogger Porta-Pak® ULV Sprayer (B&G Chemical and Equipment Co., Dallas, TX): Study notation: B&G Porta-Pak. Description: Backpack sprayer. The engine drives a blower that creates the air blast that produces the pesticide droplet spectrum at the nozzle. This sprayer has a net weight of 34 lb (15 kg), and a maximum flow rate of 5.1 oz/min (152 ml). The dimensions of this piece of equipment are 17.5 in. long × 22 in. wide × 25 in. high (44 cm long × 56 cm wide × 64 cm high). For these tests, the flow rate on both nozzles was set to 4 oz (130 ml)/min for the water-based sprays and 2.4 oz (72 ml)/min for the oil-based sprays. Two thermal fogging units were also tested as a follow-up to previously reported tests (Hoffmann et al. 2008).
- Curtis Dyna-Fog® Golden Eagle™, Model 2610, Series 3 (Curtis Dyna-Fog Ltd., Westfield, IN). Study notation: CDF Golden Eagle. Description: Handheld. The Golden Eagle utilizes a gasoline-powered 30-hp pulse jet engine or a resonant pulse to produce a thermal fog. This thermal fogger has a net weight of 19 lb (9 kg), and a maximum flow rate of 9 gal/h (34 liters). The dimensions of this piece of equipment are 52 in. long × 10 in. wide × 15 in. high (132 cm long × 25 cm wide × 38 cm high. This equipment is designed to disperse petroleum-based insecticide formulations, fungicides, germicides, disinfectants, and odor control chemicals.
- London Fog™ Eliminator (London Fog, Long Lake, MN). Study notation: LF Eliminator. Description: Handheld. The Eliminator utilizes the heat produced from a Tecumseh 2-cycle gasoline engine, with a manual recoil start, to create a dense dry fog at a flow rate of 6 gal/h (23 liters). It has a net weight of 24 lb (11 kg) with dimensions of 25 in. long × 11 in. wide × 21 in. high (64 cm long × 28 cm wide × 53 cm high). It is designed to be used with petroleum-based insecticides formulations or odor-control chemicals.

Statistical analyses

The objective of this study was not to rank or statistically separate the sprayers; therefore, no statistical analyses of the data were performed. The means and standard deviations of the measured droplet-size parameters are presented.

Table 2. Atomization parameters for water + nonionic surfactant (0.25% v/v) spray solutions.

Sprayer	Rate (oz/min)	Pressure (psi)	$D_{V0.1}$ (μm ± SD)	$D_{V0.5}$ (μm ± SD)	$D_{V0.9}$ (μm ± SD)	Vol < 20 μm (%)
Birchmeier B245: ULV Nozzle	4	Fixed	42.9 ± 1.8	77.4 ± 3.8	125.0 ± 9.3	1.63
Birchmeier B245: LV Nozzle	4	Fixed	25.0 ± 1.2	60.3 ± 2.1	98.9 ± 3.4	7.2
Arro-Gun Mozzie	4	Fixed	12.0 ± 0.5	42.6 ± 0.7	79.8 ± 1.6	20.5
ADAPCO Guardian 190ES	4	5	10.3 ± 0.3	20.9 ± 0.3	36.2 ± 0.4	46.2
ADAPCO Guardian 190ES	10	5	10.2 ± 0.2	21.5 ± 0.1	37.2 ± 0.1	45.6
B&G Porta-Pak	4	Fixed	34.2 ± 1.3	87.5 ± 3.3	149.4 ± 5.6	3.2
CDF MiniLite	4	Fixed	12.4 ± 1.2	26.4 ± 0.6	43.5 ± 0.7	28.8
CDF L30	4	Fixed	16.4 ±0.2	27.9 ± 0.0	40.0 ± 0.2	17.8
CDF Maxi-Pro 4	4	4	9.9 ± 0.2	15.5 ± 0.1	23.1 ± 0.3	78.6
CDF Maxi-Pro 4	4	5.5	12.0 ± 0.2	19.1 ± 0.1	29.7 ± 0.2	55.1
CDF Maxi-Pro 4	4	6	11.9 ± 0.3	20.0 ± 0.5	34.2 ± 0.9	50.0

RESULTS

BVA oil sprays

BVA oil is a common carrier for insecticides used in vector control spray applications. For the 9 sprayers tested with the BVA oil (Table 1), the $D_{V0.5}$ ranged from 14.8 to 61.9 μm and percent of the spray volume contained in droplets less than 20 μm (%Vol < 20 μm) ranged from 11.5% to 70.8%. For the ADAPCO Guardian 190ES sprayer, there was only a slight increase in droplet size when the flow rate increased from 4 to 10 oz/min. The CDF Maxi-Pro 4 sprayer allowed the user to vary the spray pressure from 4 to 6 psi. This increase in pressure resulted in a decrease of $D_{V0.5}$ from 20.3 to 15.3 μm and a corresponding increase in %Vol < 20 μm from 49.0% to 69.5%.

Water + 0.25% v/v nonionic surfactant sprays

The water plus nonionic surfactant (NIS) solution was used because it is a good simulant of most water-based insecticide sprays (Hoffmann et al. 2007a, 2007b), and allows the sprayers to be tested without exposing the personnel involved with this study to insecticides. For the 8 sprayers tested with the water + NIS solution (Table 2), the $D_{V0.5}$ ranged from 15.5 to 87.5 μm and percent of the spray volume contained in droplets less than 20 μm (%Vol < 20 μm) ranged from 1.6% to 78.6%. For the ADAPCO Guardian 190ES sprayer, there was only a slight increase in droplet size when the flow rate increased from 4 to 10 oz/min. When the pressure was increased from 4 to 6 psi on the CDF Maxi-Pro 4 sprayer, the $D_{V0.5}$ increased from 15.5 to 20.0 μm and the %Vol < 20 μm decreased from 78.6% to 50.0%, which was opposite of the data collected with the BVA oil for this sprayer. This is likely due to differences in the physical properties of the 2 spray solutions and should remind all applicators that one cannot assume that all spray formulations will generate the same droplet spectra for a given sprayer.

Diesel-based sprays

The CDF Golden Eagle and LF Eliminator generated sprays with a $D_{V0.5}$ of around 3.4 μm for the undiluted diesel and diesel plus insecticide solutions (Table 3). There were essentially no changes in droplet size when Fyfanon or Kontrol were added to the diesel at the dilutions used in these studies. Both sprayers also generated spray clouds in which ~100% of the spray volume was made up of droplets less than 20 μm in diameter.

DISCUSSION

The objectives of this work were to present not only information on spray-system droplet size generated by different sprayers, but also to

Table 3. Atomization parameters for diesel-based spray solutions.

Sprayer	Rate (oz/min)	Solution	$D_{V0.1}$ (μm ± SD)	$D_{V0.5}$ (μm ± SD)	$D_{V0.9}$ (μm ± SD)	Vol < 20 μm (%)
CDF Golden Eagle	4	Diesel	1.1 ± 0.0	3.4 ± 0.1	6.8 ± 0.3	100.0
CDF Golden Eagle	4	Diesel:Kontrol 1:39	1.1 ± 0.0	3.5 ± 0.1	7.2 ± 0.1	100.0
CDF Golden Eagle	4	Diesel:Fyfanon 1:91.5	1.1 ± 0.0	3.5 ± 0.1	7.2 ± 0.3	100.0
CDF Golden Eagle	4	Diesel:Kontrol 1:195	1.1 ± 0.0	3.4 ± 0.2	7.0 ± 0.6	100.0
LF Eliminator	4	Diesel	1.1 ± 0.0	3.3 ± 0.1	6.5 ± 0.0	99.7
LF Eliminator	4	Diesel:Kontrol 1:39	1.1 ± 0.1	3.6 ± 0.3	7.7 ± 1.0	99.9
LF Eliminator	4	Diesel:Fyfanon 1:91.5	1.1 ± 0.0	3.3 ± 0.1	6.7 ± 0.2	100.0
LF Eliminator	4	Diesel:Kontrol 1:195	1.1 ± 0.1	3.3 ± 0.3	6.5 ± 1.0	100.0

present a methodology by which other similar systems can be evaluated to provide applicators with sprayer-system performance data. There was a range in droplet sizes generated by the different sprayers with the different spray solutions tested. Four of the ULV units (Adapco Guardian 190ES, CDF L30, CDF Maxi-Pro, and CDF MiniLite) and the 2 thermal foggers generated spray droplet spectra with 90% of the spray volume in droplets less than 50 μm. The droplet sizes for these 2 thermal foggers (CDF Golden Eagle and LF Eliminator) were slightly smaller than those reported by Hoffmann et al. (2008); however, the differences are likely due to the differences in flow rates (10.7 vs. 4 oz/min) between these 2 studies (Brown et al. 1993). Both sprayers use thermal energy to atomize the sprays; therefore, at higher flow rates, the spray solution may not be as completely atomized (i.e., larger droplets) as when the flow rate is decreased. The other units may have been able to generate these droplet spectra under different operational conditions than those tested.

These data allow users to select the spray solution and sprayer that generates the droplet-size spectra that meet their specific spray application scenarios. For example, if an applicator is making a barrier control application where the desired result is that droplets impact and are retained on the surface, a sprayer that generates larger droplets (i.e., >40 μm) would be selected. If the application called for a spray that moves laterally downwind to impact flying insects (Brown 1968) a sprayer that generates a spray cloud with a volume median diameter of between 8 and 30 μm would be selected. This work, along with previous and future studies, provides a database detailing the droplet-size characteristics resulting from equipment, operational settings, and spray formulation combinations to aid and support decisions made by field users.

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